MIXING, PATCHINESS AND SUB-MESOSCALE DYNAMICS IN THE COASTAL ZONES

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During the contract period the work was performed on the following topics:

Description and modeling of the vertical thermohaline and turbulent structure formed by wind-induced and convective mixing on shallow sea shelves.

Detailed analysis of microstructure and turbulent measurements at the Black Sea shelf in order to study the origin and decay of stratified turbulent patches. Various scaling arguments that are commonly used for stratified turbulent patches as well as certain predictions on marine fossil turbulence were investigated in this work.

Evaluation of the effects of boundary mixing in wakes behind small islands on heat flux enhancement in the upper layer of equatorial Pacific.

A series of computer programs were developed to process the field experimental data of the first two cases. A numerical model of vertical turbulent mixing was applied to coastal waters affected by active atmospheric forcing.

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1. Introduction

During the contract period the co-P.I. (Professor Iossif Lozovatsky) and the P.I. (Professor H.J.S. Fernando) worked on the following topics:

I. Description and modeling of the vertical thermohaline and turbulent structure formed by wind-induced and convective mixing on shallow sea shelves.

II. Detailed analysis of microstructure and turbulent measurements at the Black Sea shelf in order to study the origin and decay of stratified turbulent patches. Various scaling arguments that are commonly used for stratified turbulent patches as well as certain predictions on marine fossil turbulence were investigated in this work.

III. Evaluation of the effects of boundary mixing in wakes behind small islands on heat flux enhancement in the upper layer of equatorial Pacific.

A series of computer programs were developed to process the field experimental data of the first two cases. We also modified an existing numerical model [*Lozovatsky et al.*, 1993] dealing with deep water mixing so that it can be applicable to coastal waters affected by active atmospheric forcing. Summaries of the results obtained in these works are given below. Relevant publications originated during the contract period are listed at the end of this report, and reprints are available upon request.

2. Discussion of Research Results

I. *Thermohaline and Turbulent Structure of a Shallow Shelf*

(i)   The comparison of numerical calculations and field measurements [*Lozovatsky et al.* 1995a; *Lozovatsky and Ksenofontov*, 1995] shows that a one-dimensional differential model with a novel turbulent closure can be used to predict short-period evolution of the vertical thermohaline and turbulent structures generated due to storm-induced mixing on the shallow shelf of the Black Sea.

(ii)   The model prediction of the ratio between the turbulent energy dissipation rate ε and the buoyancy flux J_B is approximately constant, namely $\varepsilon/J_B \approx 0.6$ (Figure 1). This result is in

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good agreement with the measurements of *Lombardo and Gregg* [1989] for the deepening of the upper mixed layer caused by night-time convection.
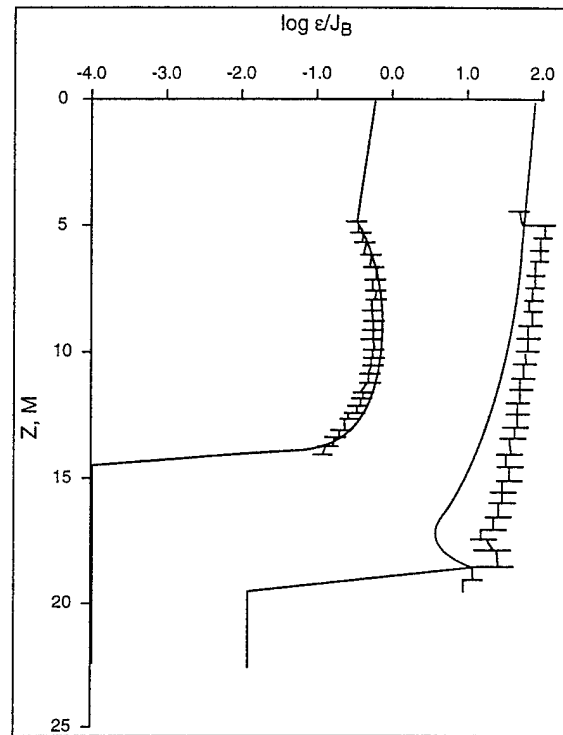

Figure 1. A comparison between the calculated profiles of the ratio e/J$_B$ and the measurements of *Lombardo and Gregg* [1989] for penetrative (left pair) and non-penetrative (right pair) convection. The last two profiles are shifted along the x-axis by 2 units.

The averaged night-time profiles of the ratio log ε/J_B (stair-like lines) measured by *Lombardo and Gregg* [1989] are plotted in Figure 1 together with the model predictions (smooth solid lines). The left pair of lines corresponds to the beginning of night convection and the right pair represents the end of early morning convection. According to our calculations and the discursive account given by *Lombardo and Gregg* [1989], the first pair of profiles relates to the penetrative convection regime whereas the second pair relates to the equilibrium state, i.e. to a non-penetrative regime. Some discrepancy between calculations and measurements was evident; for example, for the non-penetrative convection case, the buoyancy flux appeared to be overestimated. This may be due to the simplistic representation of the turbulent convective scale, which was assumed to take a constant value over the entire mixed layer. An advanced

parameterization of convective mixing in the upper layer will be undertaken in the near future. Nevertheless, the model calculations are in fair agreement with the experimental data, up to the local peak of ε/J_B at the base of the convective mixed layer; this may indicate the presence of a thin, sheared interface between fully developed turbulence and the stratified pycnocline. Turbulent entrainment at the base of the mixed layer, accompanied by a sharp decrease of the kinetic energy dissipation rate near the lower boundary of the quasi-homogeneous layer, is expected in wind-induced and convective mixing. Our numerical model successfully reproduced the development of a step-like thermohaline structure in the upper layer under the combined action of vertical mixing due to wind stress, daytime heating, and convective forcing during the beginning of autumn cooling at the Black Sea shelf.

(iii)   A parabolic decrease of the logarithm of the averaged kinetic energy dissipation rate was observed on the shallow shelf away from the surface and bottom boundary layers. [*Lozovatsky et al.*, 1996]. Mixing in the internal, weakly sheared, part of the water column was caused by random turbulent events mainly confined to turbulent patches. The state of decay of these patches should be taken into account when parameterizing turbulence in numerical models.

(iv)   The main features of vertical mixing on the shelf in the presence of upwelling circulation are quite similar to those of equatorial undercurrents in the deep ocean [*Lozovatsky*, 1995]. For example, random turbulent patches appear in the zero-mean-shear zone of the undercurrent core, just as in the central part of the upwelling cell near the coast. Turbulence is generated at the lateral boundaries of the sub-mesoscale jets or eddies in coastal currents and in equatorial undercurrents. Such turbulent "vents" or "chimneys" can cause effective vertical transports of heat, momentum, oxygen and dissolved matter across the layers of low mean vertical shear.

II. *Origin and Decay of Marine Turbulent Patches*

The time evolution of various hydrophysical parameters in turbulent patches were evaluated vis-à-vis the available scaling of stratified turbulence [*Lozovatsky and Fernando*, 1996]. The simplest governing parameters that can be used to characterize the initial state of a weakly sheared turbulent patch are the initial "mixedness" $m = 1 - N^2 / N_0^2$ and the buoyancy Reynolds

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number $Re_b = \varepsilon / 25 \nu N^2$, where N_o^2 is the mean squared buoyancy frequency outside the patch, N^2 the buoyancy frequency within a patch and ν the molecular viscosity. As shown in Figure 2, a weakly stratified layer was specified as a quasi-homogeneous patch (QHP, m = 0.85, $Re_b \approx 16$).
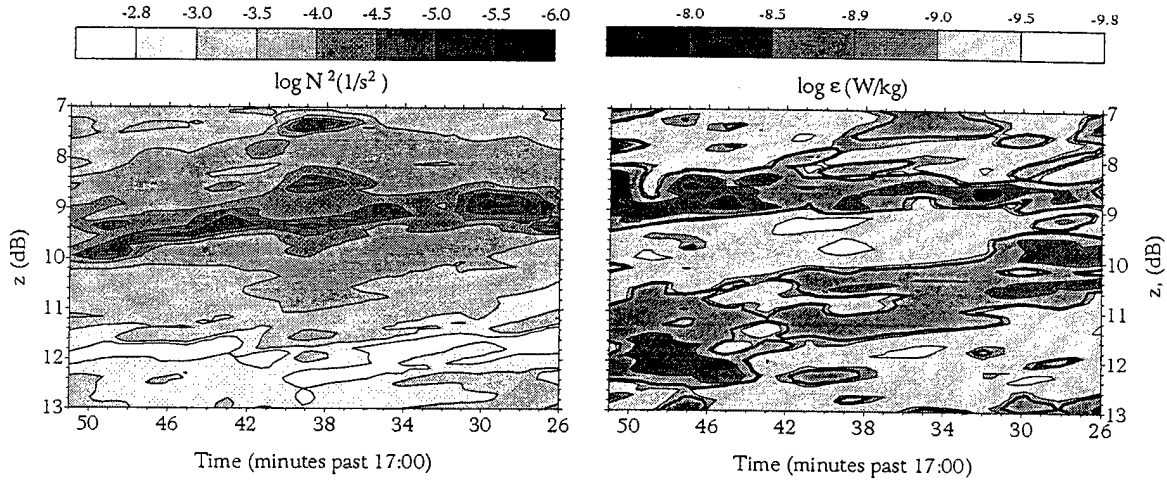

Figure 2. Vertical sections of $\log N^2(z, t)$ and $\log \varepsilon (z, t)$ in the pycnocline of the Black Sea. The quasi-homogeneous patch QHP is shown at the left panel (long dark layer). At the right panel, the active patch AP (upper dark area) and stratified active patch SAP (lower dark area) are bounded by heavy line $\log \varepsilon > - 8.9$. Various turbulent parameters, including length scales, diffusivities and mixing efficiency of these patches were analyzed.

The well-defined boundaries, signified by density interfaces, and the well-mixed turbulent interior of QHP make it particularly amenable to comparisons with published laboratory experiments and theories on isolated turbulent patches. A layer with a comparatively high dissipation rate was detected, and referred to as an active turbulent patch (AP, m = 0.95, $Re_b \approx 25$). This was mostly turbulent (based on the criterion $\varepsilon/\nu N^2 > 25$) and its properties could be compared with previous works on stably stratified turbulence. The turbulent patchy region with a stronger density stratification, named stratified active patch (SAP, m = 0.78, $Re_b \approx 0.8$), was also identified and analyzed. Substantial Thorpe displacements were found in another highly stratified region, showing the present or past significant microstructure activity. This was termed as the microstructure displacement patch (MDP, m = 0.73, $Re_b \approx 0.7$). MDP and SAP are non-turbulent, but they exhibit microstructure activity. MDP appears to represent the fossils of a

turbulent region that had been active recently and SAP appears to consist of a vigorously dissipating internal wave field.

The measurements were used to calculate parameters such as the mixing efficiency (γ), mixedness (m), mass diffusivity (K_N), scalar diffusivity (K_{sc}), activity parameter (A_G) as well as several lengthscales. The latter included the Ozmidov scale (L_N), Thorpe lengthscales (L_{Th} and L_{Th}^{max}), Boldgiano-Obukhov scale (L_*) and Ellison-Gibson scale (L_{E-G}). Wherever appropriate, the probability distribution functions and time evolution of these quantities were also evaluated. The examination of geometrical parameters and energetics of these patches showed diverse behavior, depending on the background stratification and initial energy input.

The major findings of this study are summarized below.

(i)   The probability density functions for normalized Thorpe scales L_{Th}/h_p and Ozmidov scales L_N/h_p were log-normal for QHP and AP, but for the non-turbulent MDP the distribution of L_N/h_p was found to be double log-normal (here h_p is the patch thickness).

(ii)   Mixing efficiency γ calculations exhibit two different patterns, one for AP and QHP and another for SAP and MDP. The latter was clearly double log-normal, but only 3% of the data showed $\gamma < 0.2$, which is a "canonical" value commonly used for calculating turbulent mass diffusivity $K_N = \gamma\varepsilon/N^2$. For QHP and AP, the log-normal trend was evident only in a limited range of γ ($-4.0 < \ln\gamma < 0.5$), and calculations made using log-normality gave maximum likelihood estimations of the mean $<\gamma>_{QH} = 0.73$ and $<\gamma>_{AP} = 0.8$; about 40% of the samples in AP and QHP showed $\gamma \leq 0.2$.

The overweight of high γ samples in SAP and MDP points to the presence of fossil turbulence [*Gibson*, 1980] in these patches. The dependence between the activity parameter $A_G = 1/\sqrt{13\gamma}$ and buoyancy Reynolds number $Re_b = 25\varepsilon/\nu N^2$, however, led to a cloud of samples in the so-called "fossil turbulence quadrant" $[-2 < \log Re_b < 0$ and $-2 < \log A_G < 0]$ (Figure 3). All these samples underlie the straight line described by $A_G \cong c_A Re_b^{1/2}$, where $c_A \approx 1$. This straight line is likely to characterize a "background" turbulence state with a constant value of the mixing Reynolds number $R_m \equiv K_{sc}/\nu$, which is equal to $R_m^0 = 2$.

More importantly, the approximate constant scalar diffusivity ($R_m \approx 20$) was also found in the active patch.
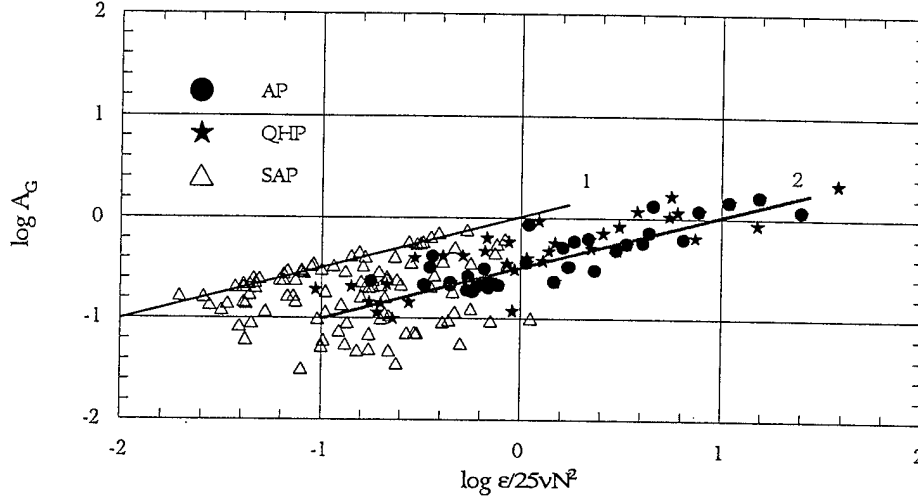

Figure 3. Hydrodynamic phase diagram, showing dependence between the logarithms of activity parameter A_G and buoyancy Reynolds number $R_b = \varepsilon / 25\nu N^2$ for three turbulent patches. Line 1 corresponds to the "mixing" Reynolds number $R_m^o = 2$. For line 2, $R_m^o = 20$.

(iii) The time evolution of the main turbulence parameters differed significantly for different ambient stratification conditions. Lengthscale calculations showed that for turbulent patches (AP and QHP), $L_N > L_{E-G} > L_{Th}$ and for non-turbulent patches $L_{Th} > L_{E-G} > L_N$. In AP, all turbulent scales decreased exponentially during the decay process. The decay time constant λ_τ had the largest value for the normalized Ozmidov scale $L_N / h_p \sim e^{-\lambda_\tau t}$ ($\lambda_\tau \approx 0.1 N_o$, $N_o = 0.02$ s^{-1}); λ_τ was half the above value for the Ellison-Gibson scale. The normalized r.m.s. Thorpe displacement scale also decreased in time, which is inconsistent with the fossil turbulence model of *Gibson* [1980]. In QHP, L_{Th}/h_p was always smaller than L_N/h_p, which also contradicts the fossil turbulence theory, in spite of L_{Th}/h_p remaining approximately constant while L_N/h_p decreased in time. Such a ratio between the turbulent scales appears to be more appropriate for a decaying, partially mixed, stably-stratified layer rather than for a fossil turbulence state evolving from an individual overturn event.

All turbulent scales in the MDP and SAP were found to have approximately constant mean values. The observed constant ratio between the r.m.s. Thorpe displacement scale and the patch thickness ($L_{Th}/h_p = 0.27$) agrees well with the laboratory experimental results of *De Silva and Fernando* [1992] which was taken for a continuously forced stratified turbulent patch. Small values of L_N/h_p and L_{E-G}/h_p observed in MDP and SAP can be attributed to the very small turbulent eddies near the patch boundaries, which are responsible for slow turbulent entrainment of stratified fluid into the weakly-mixed turbulent patch. It is a completely different mixing process compared to high-amplitude overturns caused by K-H instability or convective instability of internal waves. This hypothesis should be confirmed or rejected based on detailed field and laboratory measurements.

(iv)   An attempt was made to compare laboratory and field measurements of the Thorpe scale in decaying turbulent patches.
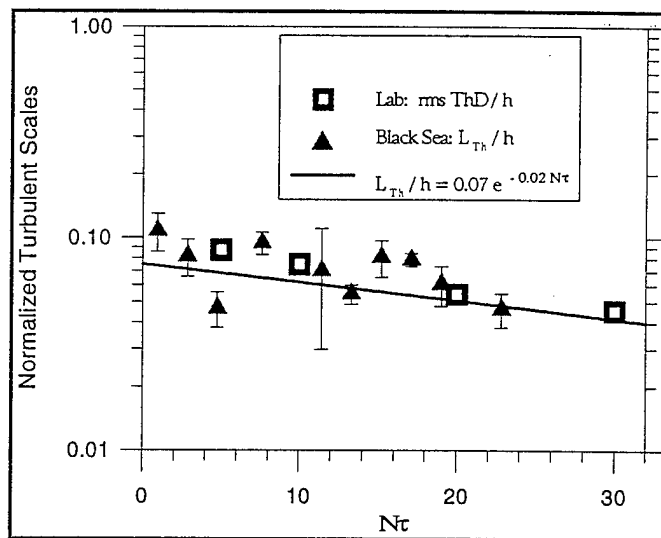

Figure 4. Time evolution of the normalized Thorpe scale in QHP (triangles are field data of $<L_{Th}/h_p>$, averaged over the patch thickness); squares are from the laboratory experiment.

These efforts led to quite encouraging results, which are presented in Figure 4. Laboratory data reasonably describe the time evolution of the normalized Thorpe scale in a quasi-homogeneous turbulent marine patch. An exponential decrease of L_{Th}/h_p with nondimensional time Nt was noted in both cases.

(v)   The results of normalized Thorpe scales L_{Th}/h_p taken from AP and QHP regions together with the previous observations of *Dillon* [1982], *De Silva and Fernando* [1992], *Gibson et al.* [1993], *Peters et al.* [1995] clearly indicate the dependence of L_{Th}/h_p on background conditions (Figure 5).
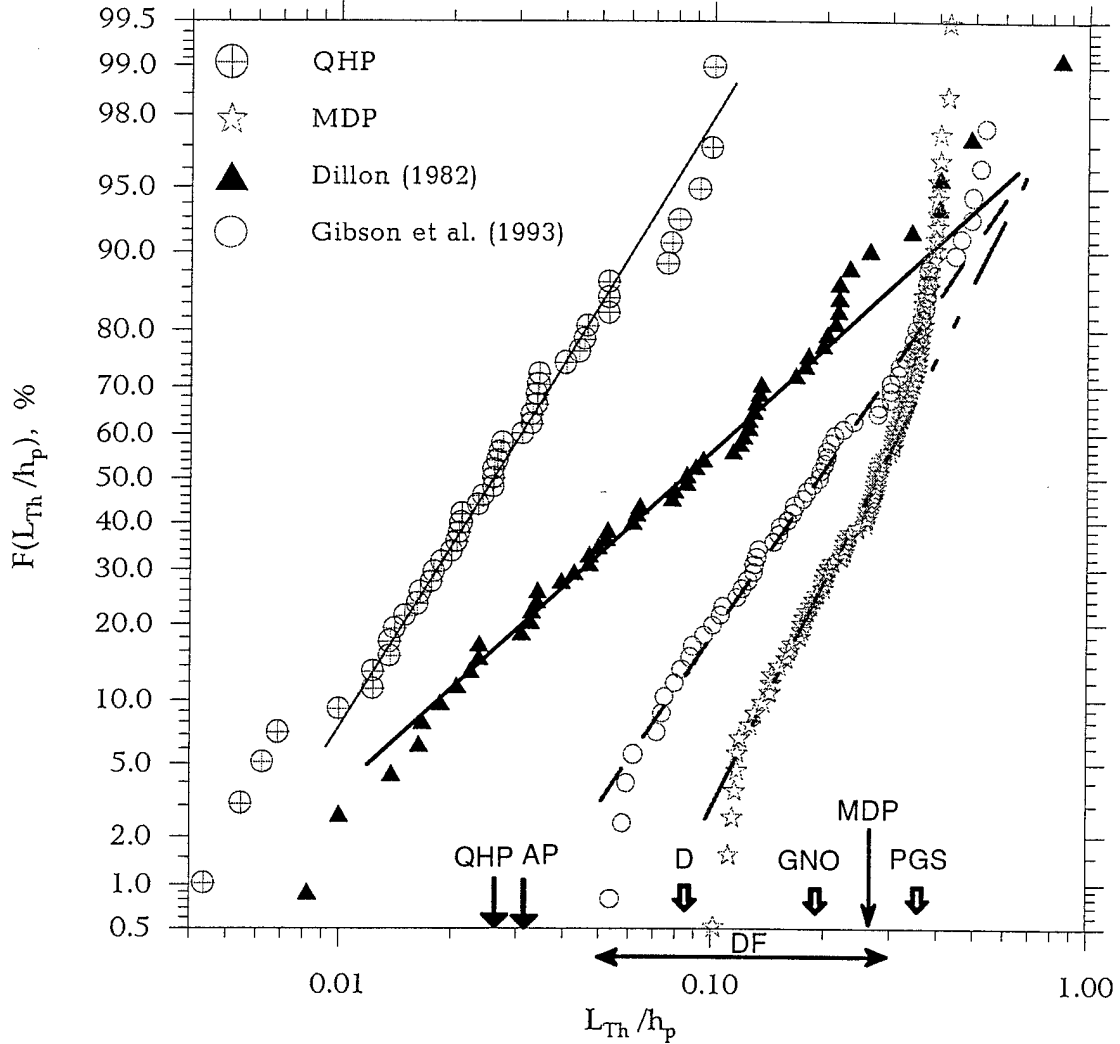

Figure 5. The cumulative distribution functions of the normalized r.m.s. Thorpe scales for QHP and MDP. $F(L_{Th}/h_p)$ was also calculated for the data presented by *Dillon* [1982, D, Tables A and B] and *Gibson et al.* [GNO, 1993, Table 2]. The median values $m_d(L_{Th}/h_p)$ for different data sets, including equatorial measurements of *Peters et al.* [1995, PGS], are shown by the arrows along the horizontal axis. Laboratory measurements of L_{Th}/h_p obtained by *De Silva and Fernando* [1992, DF] for various values of the mixedness parameter are in the range marked by the horizontal arrows.

On dimensional grounds, L_{Th}/h_p was proposed to be a function of the mixing Reynolds number R_m, the patch Richardson number $Ri_p = N^2 h_p^4 / K_{sc}^2$ and the buoyancy frequency ratio N/N_o, where N_o is the background buoyancy frequency.
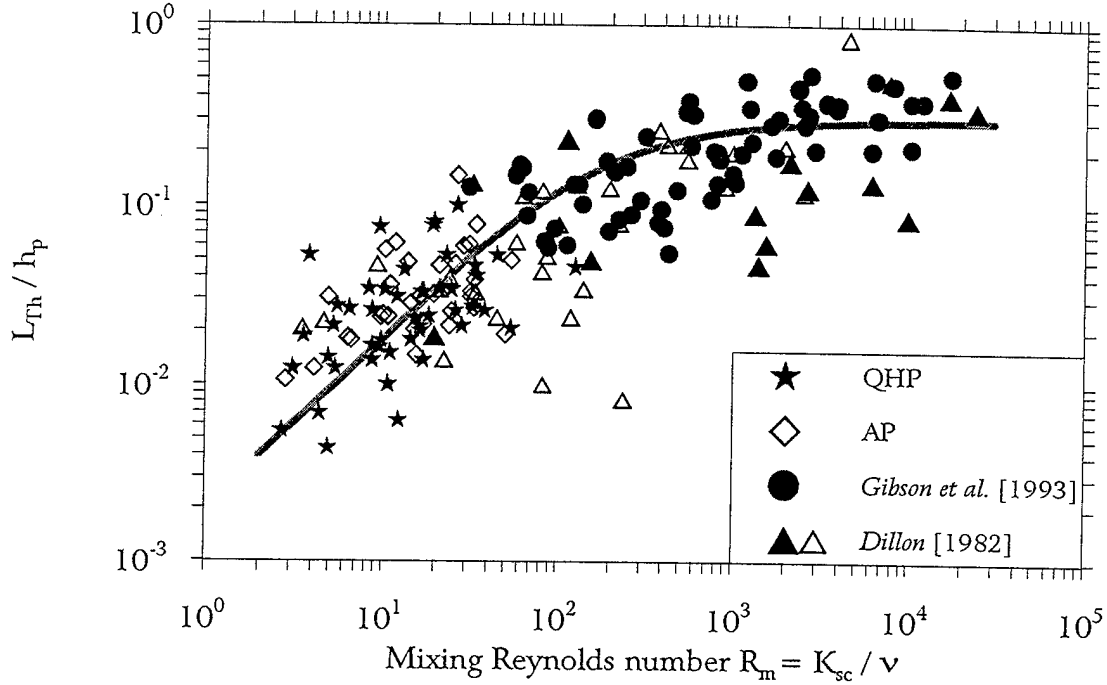

Figure 6. The dependence of the normalized Thorpe scale L_{Th}/h_p on the mixing Reynolds number R_m for different regions. Solid line is given by the formula $\dfrac{L_{Th}}{h_p} = \dfrac{\hat{L}_{Th}^m}{1 + R_m^{cr} / R_m}$, where $\hat{L}_{Th}^m = 0.3$ and $R_m^{cr} = 150$.

The observations confirmed this proposal, and showed that L_{Th}/h_p is an increasing function of R_m when $R_m < R_m^{cr} \approx 150$ and a constant ($L_{Th}/h_p \approx 0.3$) for $R_m > R_m^{cr}$ (Figure 6). For a given R_m, L_{Th}/h_p seems to decrease with Ri_p.

III. *Effects of Boundary Mixing in Wakes Behind Small Islands*

Air-sea interaction in the equatorial Pacific significantly depends on heat and energy fluxes, both in the upper oceanic boundary layer occupied by the eastward equatorial surface current (ESC) and in the zero-mean shear core of the westward undercurrent (EUC) in the

pycnocline. These currents permanently produce extensive boundary mixing around small equatorial islands, for example, Baker and Howland Islands located at 176° 12' W. It was found [Lilover et al. 1993, *Lozovatsky et al.*, 1995b; *Lozovatsky*, 1996] that the turbulent wakes behind these islands strongly enhance the vertical heat flux in the upper quasi-homogeneous layer (see Figure 7).
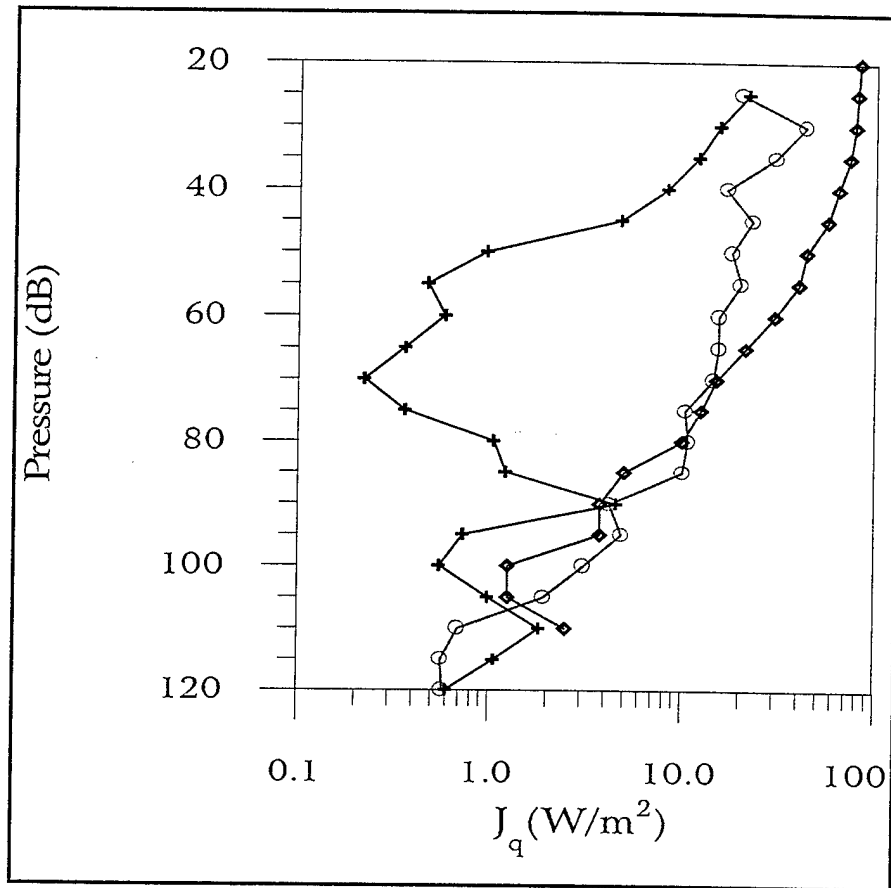

Figure 7. Averaged profiles of turbulent heat flux J_q near the equator at 14 miles west (circles) and 30 miles east (crosses) of Baker Island. The averaged profile of $J_q(z)$ at 140°W, taken from *Moum et al.* [1989], is shown by rhombuses. The dramatic mixing enhancement in the wakes of the equatorial islands can be clearly identified.

In the depth range between 40 and 90 m, the heat flux in the wake exceeded the background flux at the same depth range by a factor of 20 - 50, approaching the values of J_q that have been found in the eastern Pacific [*Peters et al.*, 1988; *Moum et al.*, 1989]. At shallower depths the difference is not so evident owing to intensive nocturnal convective mixing. The nighttime averaged dissipation rate $<\varepsilon>$ at 176^0 W (east of Baker Island) was in the range of 10^{-7} - 10^{-8} W/kg in the

sub-surface layer ($z \approx 10 - 30$ m), decreasing exponentially to $3 \cdot 10^{-9}$ W/kg at the base of the mixed layer. At the intermediate depths, in the upper quasi-homogeneous layer ($z \approx 45 - 90$ m), the turbulent dissipation was small, with a mean value of about 10^{-9} W/kg.

On the other hand, west of the island $<\varepsilon>$ achieved a maximum of 10^{-7} W/kg in the center of the upper mixed layer, due to the advection of turbulent energy in the wake of the ESC produced by boundary mixing. No remarkable decrease of turbulent activity in the upper-layer wake was found at least for 25 km downstream. Therefore, by considering the large number of islands in the western equatorial Pacific and the permanent character of the equatorial currents, it is possible to hypothesize that there is significant enhancement of the vertical turbulent transport in the upper layer downstream of the ESC. A similar enhancement can be expected in the pycnocline downstream of the EUC.

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Lozovatsky, I. D., and H. J. S. Fernando, Observations of turbulence in marine stratified layers , *J. Geophys. Res.*, 1996, (submitted).

Papers in Preparation

Lozovatsky, I. D., A. Yu. Erofeev, and T. Dillon, Thermohaline variations on the shallow Black Sea shelf following a series of fall mild storms, 1996, (in preparation).

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Lozovatsky, I. D., A. Yu. Erofeev, V. N. Nabatov, and M. Lilover, Turbulent heat flux across the equatorial undercurrent and in the wakes of small equatorial islands in the western Pacific, *Proc. of the Int. Sci. Conf. on the Ocean Global Atmosphere (TOGA) Prog.*, WCRP-91, WMO/TD No.717, **1**, 532-536, 1995.

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